the "grand-tour mission" in which a spacecraft would visit in succession Jupiter, Saturn, Uranus, and Neptune, an operation that may be well under way before it would be necessary to set out on the Halley rendezvous.

As you know, there are various opinions about space research, but I venture to think that Halley would have been in favour of such a mission, and I will conclude by expressing the hope that when 1986 comes and brings Comet Halley back, the space-fleets of all nations will be out to welcome it, to the greater glory of the illustrious Halley himself.

Thank you, Mr. Vice-Chancellor.

THE EVOLUTIONARY STATUS OF BLUE SUPERGIANTS

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Introduction. Modern approaches to stellar evolution rely on a close interplay between theory and observation. The present paper is a unified attempt to account for the properties of the blue supergiants by bringing together the available theoretical and observational evidence related to these stars. For an introduction, it is useful to review briefly the possible modes of theoretical evolution for single and double stars of high mass.

Modern models of massive stars with unmixed or semiconvectively mixed intermediate zones indicate that helium burning will commence in the stellar core while the star is in the red-supergiant stage; the blue-supergiant phase of helium burning occurs subsequently (see Stothers and Chin[1] and Stothers[2]). Since the radius of a red supergiant is much greater than that of a blue supergiant, we should expect an absence of short-period binaries among blue supergiants which have returned from the red-supergiant tip. On the other hand, stellar models with large convectively mixed intermediate zones commence helium burning in the core while they are still on the blue side of the H–R diagram.[3,4,5] In this case, we should expect a large number of short-period binaries among the blue supergiants.

The orbital period at which an evolving star in a binary system just fills its Roche lobe has been calculated by Plavec[6] on the basis of evolutionary tracks given by Iben.[3,7] The limiting periods for blue and red supergiants, respectively, are approximately 10 and 400 days at 9 $\mathfrak{M}_{\odot}$, 40 and 1000 days at 15 $\mathfrak{M}_{\odot}$. Observational data for B5 Ia and M2 Ia stars yield 20 days and 2000 days, respectively, in satisfactory agreement. The effects of differing mass ratios and orbital eccentricities on the theoretically predicted periods may be ignored as they are relatively small.

Theoretical calculations by several groups[8,9,10] indicate that a star which expands to fill its Roche lobe after the exhaustion of hydrogen in its core will suffer severe mass loss, causing it to move to the vicinity of the helium-burning main sequence rather than to the supergiant region of the H–R diagram.

Theoretical evolutionary tracks. A prerequisite for a meaningful comparison of observational and theoretical data is the identification of a star whose core has reached a given stage of evolution with a particular type of star. The composite H–R diagram prepared by Feast[11] for four clusters in which stars of approximately 15 $\mathfrak{M}_\odot$ are just leaving the main sequence shows a well-defined gap in absolute magnitude between the supergiant stars and those of fainter luminosity class. The theoretical tracks for 15 $\mathfrak{M}_\odot$ show[3,12,13] that the exhaustion of hydrogen in the core is followed by a phase of helium-core contraction during which rapid expansion of the envelope results in a corresponding increase in the visual luminosity. Stars lying above the gap will thus be in the core helium-burning phase.

Evolutionary tracks[7,14] for 9 $\mathfrak{M}_\odot$ and 30 $\mathfrak{M}_\odot$ also have a phase of rapid brightening following the exhaustion of hydrogen in the core. The corresponding gaps in the colour-magnitude diagrams of appropriate clusters (NGC 3766[15], Sco OB1[16]) are similarly well defined. However, in the very young group Sco OB1, the gap does not appear between supergiant and class II–V stars, but rather between the two supergiant classes Ia and Ib.

It follows that there is not a unique relationship between luminosity class and evolutionary stage of the stellar core. A class Ib star of very high mass might still be near the end of core hydrogen burning (see also Refs. 12 and 17.)

TABLE I

Binary Frequency among Supergiants

		(Percentages)				
Type	(1)	(2)	(3)	(4)	*Number* (1)	*Number* (2)
O		—	—	—		—
B	5	10	10	—	65	45
A		14	8	—		14
FG	27	15	6	—	62	10
K	19	10	10	—	36	5
M		25	0	12		8

(1) Figures by Jaschek and Jaschek[19].
(2) Massive supergiants only—see text.
(3) As (2), excluding eclipsing binaries and stars with composite spectra.
(4) Based on the frequency of composite spectra among 24 M-type supergiants in clusters and associations[2].

A further ambiguity in the evolutionary stage of a single star results from the fact that a star will evolve through the blue-supergiant region of the H–R diagram during the helium-core contraction phase on its way to ignite helium as a red supergiant. This phase lasts about 3×10^4 years compared to 1×10^6 years for the lifetime of core helium burning, in the case of a star of 15 $\mathfrak{M}_\odot$.

These conclusions are strengthened by three properties of the blue stars lying above the gap in young clusters. First, the masses of the majority of these stars derived from the theoretical mass-luminosity relation for core helium-burning stars agree very well[12,17] with the masses of stars on the main-sequence turnups derived from the observational (or theoretical) relationship between mass and spectral type for main-sequence stars. Secondly, the approximate constancy of bolometric magnitude with spectral type for most of these stars in a number of individual clusters[12,17] agrees with the predicted trend of the evolutionary track for core helium-burning stars. Thirdly, the decreasing percentage of early spectral types found among these stars in clusters of increasing age[12,17] agrees with the theoretical prediction of a cooler maximum effective temperature which is attained in core helium-burning stars of lower mass.

Binary statistics. The distribution of binary frequency with spectral type among stars selected from the Wilson Catalogue[18] as supergiants[19] (denoted by the "c" spectral characteristic) supported the idea that evolution proceeds from red to blue during core helium burning[2]. The Jascheks' selection of supergiants can be improved on in several respects now.

(1) There seems no good reason to exclude emission line stars. Most B supergiant binaries have emission lines (Table II).

(2) Most of the "c" stars in the Wilson Catalogue have MK classes[20], allowing the exclusion of several stars of lower luminosity class.

(3) The Ib stars of spectral type A0–K4 should be excluded since most are of relatively low mass, as indicated by their presence in such clusters as NGC 6067[21] and the α Per cluster[22], and fall below the limit $M_{\rm bol} = -6$ suggested by the data for groups containing M supergiants[2].

(4) A number of stars previously suspected to be binaries are now known to have intrinsic velocity variations and should be excluded.

Table I contains: the binary frequencies given by the Jascheks; the revised figures (in which binaries unconfirmed by orbits, eclipses, or composite spectra are given half weight); the revised figures excluding eclipsing binaries and stars with composite spectra, which may lead to a selection effect in favour of late-type binaries; and the figure for binary frequency among M supergiants in clusters and associations, based on the occurrence of composite spectra among stars with luminosity classification[2]. The last two columns give the total numbers of stars of each type used in deriving the binary frequencies of columns 1 and 2, respectively.

TABLE II

Data for eight blue supergiant binaries

HD	*Var. Star*	*P (days)*	*Spectral Type*
36371		655	B5 Iab
62623		138	A2 Iabe
72754[24]	Var	34	B1·5 Ie
152667[25]	Var	7·8	B0·5 Ia[16]*
166937	μ Sgr EA	180	B8 Iaep
181615		138	B8 I? *He* star[29]
190967	V448 Cyg EB	6·5	B1 Ib–II + O9·5
211853		6·7	WN6 + B0: I:

*Walker[25] gives B0 Ie.

The approximate constancy of the binary frequency with spectral type (10 per cent) supports the idea that evolution proceeds from red to blue among core helium-burning stars. The data for blue supergiant binaries with known orbits, discussed in the next section, are not entirely consistent with this.

Blue supergiant binaries. Data for six blue supergiant binaries from the *Sixth Catalogue of Binary Star Orbits*[23] and for another two from unpublished Radcliffe Observatory material[24,25] are given in Table II. Three of these stars, all possibly lying in stellar associations, have periods which are very short even for helium-core contracting stars. The contact binary V448 Cyg is not well separated from the main sequence in the young cluster NGC 6871[26]. The possible evolutionary states of this star have been discussed by Sahade[27]. HD 152667 is the faintest star of luminosity class Ia in Sco OB1[16]. The Wolf-Rayet component of HD 211853, a system which may lie in the Cep OB1 association[28], is possibly the result of mass loss caused by a close companion[9]. The helium star HD 181615 may also have had its outer layers stripped by its close companion[29]. The last two stars are excluded from further discussion.

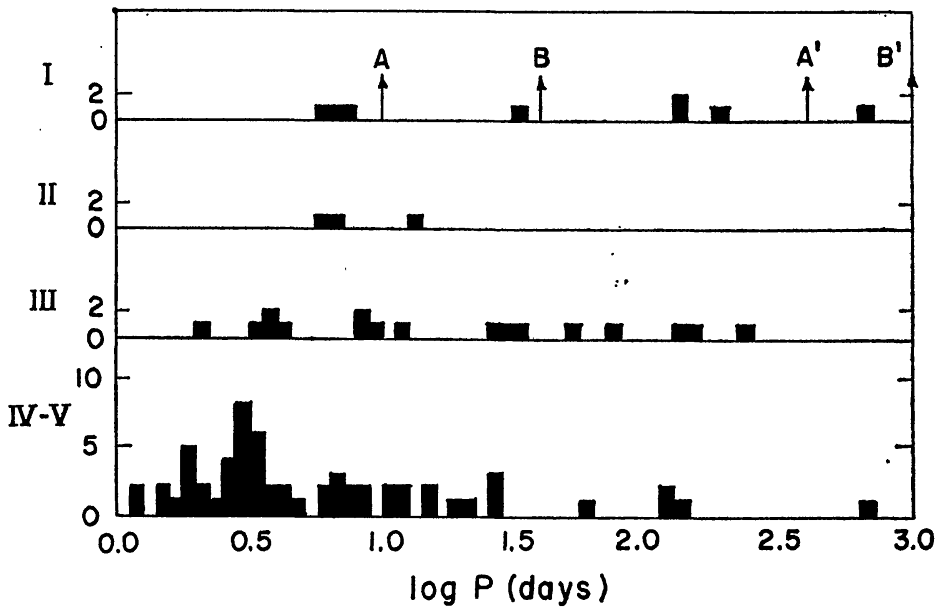

FIG. 1

Histograms of period distributions for binary systems containing supergiants of spectral type earlier than A3 or stars of luminosity class II, III or IV–V and spectral type earlier than B3. A and A[1] are the theoretical limiting periods for blue and red supergiants of 9 $\mathfrak{M}_\odot$, while B and B[1] are the corresponding periods for 15 $\mathfrak{M}_\odot$.

Main-sequence stars of mass greater than about 10 $\mathfrak{M}_\odot$ have spectral types earlier than B3. The Sixth Catalogue contains orbital elements for 61 early-type stars of luminosity class IV–V, 17 of class III, and 3 of class II. Fig. 1 gives histograms of the orbital periods for each luminosity class.

The observational and theoretical lower limits to the periods are in satisfactory agreement for the stars of luminosity classes II–V. The periods of the normal supergiants, with the possible exception of HD 36371, are such that they cannot have passed through the red-supergiant stage. These stars are therefore available for comparison with single blue supergiants, of which a substantial proportion is expected to be in the core helium-burning phase.

The discussion in the last section, based on semi-independent statistical data, would lead one to expect that most of the blue supergiant binaries have long periods. The actual preponderance of short periods, taken at face value, would suggest that a larger proportion of B supergiants than predicted theoretically has not been to the red-supergiant tip. The situation may arise from severe observational selection in favour of stars with large velocity ranges.

An additional point is that most of the binaries of known orbit are of luminosity class Ia or Iab, whereas the proportion of velocity variables in the Wilson Catalogue does not change significantly from Ia to Ib. There is an apparent conflict between this situation and the expectation that the main source of short period binaries would be stars of very high mass near the end of core hydrogen burning and stars in the helium-core contraction stage, which would be expected to be preferentially of class Ib.

It is also worth considering whether the supergiant binaries contain a large proportion of stars which are peculiar, in the sense of not falling into one of the groups expected theoretically. A possibility is that these stars are, or have been, losing mass. Most of the binaries in Table II have emission lines; where detailed spectroscopic information is available this has a P Cygni type profile, except in the case of HD 72754.

Andrews[30] has measured $H\alpha$ strengths for HD 36371, 152667, 166937 and 190967. All show stronger emission or weaker absorption than the average for their spectral type though not to the extent of a strong P Cygni-type star. This may indicate increased mass loss resulting from the presence of a companion. Departures from LTE may cause $H\alpha$ emission in normal supergiant stars[31] but a P Cygni profile is not expected in that case.

The main conclusion of this section is that improved statistical data on the binary properties of early-type supergiants are required.

Nitrogen abundances. Wallerstein[32] has suggested that the observed nitrogen abundances provide a useful test of the evolutionary status of blue supergiants: a star which has already been a red supergiant should exhibit an overabundance of nitrogen because the deep convective envelope in the latter phase will bring the products of the *CN* cycle of core hydrogen burning to the surface. The test could be made by comparing the nitrogen abundances in short-period binary stars with those in single stars, most of which are expected to have returned from the red-supergiant region. It would be advisable to restrict the spectroscopic study to stars of luminosity class Ib in order to avoid the difficulties resulting from the very extended atmospheres of Ia supergiants. For Ib blue stars, we would expect a normal abundance of nitrogen in all short-period binaries (in the absence of mass exchange between the components) as well as in high-mass stars and those low-mass stars evolving though the helium-core contraction phase, while low-mass stars in the core helium-burning phase (the majority of the single stars) should show an overabundance of nitrogen.

The available observational evidence is very scanty. Only two stars—both single—have been analyzed in detail, but by the use of conventional techniques. The star ζ Per (B1 Ib) does not show[33] a nitrogen overabundance with respect to the mean of early-type main-sequence stars,[34] but it appears to lie at the tip of the main-sequence turnoff in the Per OB2 association[35]. The star α Cyg (A2 Ia) has been analyzed by Groth[36], Taffara[37] and Przybylski[38]. These authors derive rather different physical parameters for the atmosphere but Groth and Taffara agree in giving $N/O \sim 1$, while Groth also finds $N/C \sim 5$ (Przybylski did not estimate an abundance for N). This is similar to the result found in the evolved giants of lower mass, α Per and β Aqr[39]. The derived effective temperature and surface gravity[37] of α Cyg yield log $(\mathfrak{M}/L) = -3\cdot8$ which, combined with the theoretical mass-luminosity relationship for core helium-burning supergiants[2], implies a mass of $\sim 13\ \mathfrak{M}_\odot$. These results for only one star should not be regarded as conclusive, especially in view of present uncertainties in the atmospheric structure in Ia supergiants.

Other tests of the direction of evolution. While attempts to detect a slow secular change in the effective temperature of blue and yellow supergiants have so far been unsuccessful[40], the relative numbers of supergiants in different colour and luminosity groups have been used successfully, in conjunction with theoretical stellar models, to infer that evolution during core helium burning does proceed from red to blue[2,41]. Semi-empirical masses of several variable red supergiants in associations, derived by the pulsational Q-value method, also require that these stars be in the early stages of core helium burning[42].

Since normal stellar evolution results in an average brightening of the stellar luminosity, the relative brightness of blue and red supergiants also provides a test of the direction of evolution. Table 1 of Stothers[2] contains 58 blue and red supergiants with known absolute magnitudes, being members of galactic clusters and associations (omitting the uncertain outer group of Per OB1). Adopting bolometric corrections due to Johnson[43], one finds the peak of blue-supergiant and red-supergiant luminosity functions occurring at $M_{\mathrm{bol}} = -7\cdot5$ (36 stars) and $M_{\mathrm{bol}} = -6\cdot7$ (22 stars), respectively. Unpublished bolometric corrections for red supergiants by T. A. Lee[44] are virtually the same as Johnson's, while the most recent determinations of the bolometric corrections for blue supergiants tend to increase the difference in $\langle M_{\mathrm{bol}}\rangle$. If the difference in brightness, $0^{\mathrm{m}}\cdot8$, is attributed to evolutionary effects, then the most common mass is $\sim 15\mathfrak{M}_\odot$, the amount of brightening is approximately correct, and evolution proceeds from red to blue.*

In conclusion, there is clearly a need for more information on the statistics, binary nature, and chemical composition of the atmospheres of supergiants, especially for stars whose membership in clusters or associations provides independent information on their mass and evolutionary status.

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*Individual clusters or associations probably should not be used for this test because a range in supergiant luminosities (masses) is occasionally observed owing to variations in stellar times of formation. But the cluster nuclei observed by Schild[17] show the predicted evolutionary effect.

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LIMITS ON THE POSITIONAL CHANGES OF N-GALAXIES

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It is widely believed that the radio N-galaxies are closely related to quasars[1,2]. Several unsuccessful attempts have been made to detect either proper motions[3,4,5] or short-term positional changes[6] of quasars. Detection of proper motions would rule out a cosmological interpretation of the red shifts, since apparent positional changes could occur if the light, which is

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